KamLAND update

KamLAND: Kamioka Liquid-Scintillator Anti-Neutrino Detector

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Essentials of Neutrino Oscillations

\[ m_2 c^2 \]
| \( \nu_e \rangle = |\psi_{\nu_e} (0) \rangle = \cos \theta |\nu_1 \rangle + \sin \theta |\nu_2 \rangle \]

\[ m_1 c^2 \]
| \( \psi_{\nu_e} (t) \rangle = \cos \theta e^{-\frac{i m_1 c^2 t}{\hbar}} |\nu_1 \rangle + \sin \theta e^{-\frac{i m_2 c^2 t}{\hbar}} |\nu_2 \rangle \]

\[ P_{ee} (t) = \left| < \psi_{\nu_e} (0) | \psi_{\nu_e} (t) > \right|^2 = \left| \cos^2 \theta e^{-\frac{i m_1 c^2 t}{\hbar}} + \sin^2 \theta e^{-\frac{i m_2 c^2 t}{\hbar}} \right|^2 \]

\[ P_{ee} (t) = 1 - \sin^2 2\theta \sin^2 \left( \frac{(m_2 - m_1)c^2}{2\hbar} t \right) \]

\[ t = \frac{t_{lab}}{\gamma} \approx \frac{L}{\gamma c} \quad \gamma = \frac{E}{mc^2} \quad m = \frac{m_1 + m_2}{2} \]

\[ P_{ee} (t) = 1 - \sin^2 2\theta \sin^2 \left( \frac{(m_2^2 - m_1^2)c^4}{4\hbar^2} \frac{L}{E} \right) \]

\[ P_{ee} (t) = 1 - \sin^2 2\theta \sin^2 (1.27 \Delta m^2 \frac{L}{E}) \]
20% of world nuclear power

\(~ 70 \text{ GW}~

86% of events from 175 ± 35 km

Kashiwazaki

Kamioka
Long-Baseline Reactor-Anti-Neutrino Experiments
At the time the LRP was being drafted

- The case for neutrino flavor change was compelling
- The case for neutrino oscillations was growing stronger
- Evidence of large mixing angles was mounting
$\bar{\nu}_e + p \rightarrow e^+ + n$

$\tau \approx 200 \mu s$

$n + p \rightarrow d + \gamma(2.2 \text{ MeV})$
KamLAND was rapidly deployed

- September 2000
- October 1999
- September 2000 Data Taking
- January 2002 Data Taking
3.2 ton water veto
Prompt $E \sim 3.2 \text{ MeV}$

Delayed $E \sim 2.22 \text{ MeV}$

$\Delta t \sim 110 \mu\text{sec}$

$\Delta R \sim 0.35 \text{ m}$

Candidate Neutrino Event
KamLAND’s first reactor result

First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance

(most cited paper in physics, 2003)
Reactor Neutrino Physics 1956-2003

$N_{\text{obs}}/N_{\text{exp}}$

Distance to Reactor (m)

- ILL
- Savannah River
- Bugey
- Rovno
- Goesgen
- Krasnoyarsk
- Palo Verde
- Chooz
- KamLAND
Is the Neutrino Spectrum Distorted?

2-ν oscillation: best-fit

No oscillation, flux suppression

\[ \chi^2 / 8 \text{ d.o.f.} = 0.31 \]

Data and best oscillation fit consistent at 93% C.L.

Data and best oscillation fit consistent at 53% C.L. as determined by Monte Carlo
KamLAND's second reactor result

Measurement of Neutrino Oscillation with KamLAND: Evidence of Spectral Distortion
2004 Data Set

Is the Neutrino Spectrum Distorted?

\[ \chi^2 \text{/ 11 d.o.f} = 13 \]
Backgrounds

1. Random coincidences $2.69 \pm 0.02$ events

2. Spallation Backgrounds from neutrons and delayed beta emitters $^9\text{Li}$ and $^8\text{He}$ $4.8 \pm 0.9$ (dead time 9.7%)

2 sec

$2 \text{ msec} + 2 \text{ sec in 6 } m\phi \text{ cylinder}$

3. $^{210}\text{Po} \alpha \rightarrow ^{13}\text{C}(\alpha, n)^{16}\text{O}^*(\sim6 \text{ MeV}) \text{ and}$

$^{13}\text{C}(\alpha, n)^{16}\text{O} \rightarrow ^{12}\text{C}(n, n')^{12}\text{C}^*(4.4 \text{ MeV}) \ 10.3 \pm 7.1 \text{ events}$

Total: $17.8 \pm 7.3$
## Systematic Uncertainties

\[ E > 2.6 \text{ MeV} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial mass ratio</td>
<td>4.7 %</td>
</tr>
<tr>
<td>Energy threshold</td>
<td>2.3 %</td>
</tr>
<tr>
<td>Efficiency of cuts</td>
<td>1.6 %</td>
</tr>
<tr>
<td>Live time</td>
<td>0.06 %</td>
</tr>
<tr>
<td>Reactor power</td>
<td>2.1 %</td>
</tr>
<tr>
<td>Fuel composition</td>
<td>1.0 %</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ cross section</td>
<td>0.2 %</td>
</tr>
</tbody>
</table>

Total uncertainty: 6.5 %
Looking for the oscillation effect

\[ \left| \langle \psi_{\nu_e} (t) | \psi_{\nu_e} (0) \rangle \right|^2 = 1 - \sin^2 (2\theta) \sin^2 \left( \frac{(m_2 - m_1)c^2}{2\hbar} t \right) \]

\[ P_{ee} = 1 - \sin^2 (2\theta) \sin^2 \left( 1.27 \frac{(m_2^2 - m_1^2)L}{E} \right) \]

\[ L = c \cdot t_{\text{lab}} \quad t_{\text{restframe}} = \frac{t_{\text{lab}}}{\gamma} = \frac{m}{E} t_{\text{lab}} \]
Observing the oscillations in the neutrino rest frame
KamLAND Correlation of Count Rate and Reactor Power

Reactor at the core of the earth?
Observation of Geoneutrinos

Experimental Investigation of Geologically Produced Antineutrinos with KamLAND
Geo-Neutrino Signal

U/Th decays in the Earth produce radiogenic heat (40-60% of 40TW)

\[ E_{\nu(geo)} < 2.49 \text{ MeV} \]
The Earth is made up of five basic regions: Core, Mantle, Oceanic crust, and Sediment.
Heat flow from the earth determined from bore-hole temperature gradients.

44.2 ± 1.0 TW or

31 ± 1 TW (same data)

Radiogenic heat should contribute. Using the composition of chondritic meteorites expect

U/Th/K

20ppb/80ppb/240ppm

8 TW/8 TW/3 TW

Puzzle:

19 TW ≠ 44.2 TW or 31 TW
Neutrino Spectrum from K and the U and Th chains

KamLAND Threshold
Reference Model

<table>
<thead>
<tr>
<th></th>
<th>U [ppm]</th>
<th>Th [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment</td>
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<td></td>
</tr>
<tr>
<td>Continental</td>
<td>2.8</td>
<td>10.7</td>
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<tr>
<td>Oceanic</td>
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<td>6.91</td>
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<tr>
<td>Continental Crust</td>
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<tr>
<td>Upper</td>
<td>2.8</td>
<td>10.7</td>
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<td>Middle</td>
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<td>Lower</td>
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<tr>
<td>Oceanic Crust</td>
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<td></td>
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<tr>
<td>Mantle</td>
<td>0.012</td>
<td>0.048</td>
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<tr>
<td>Core</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

![Graph](image)
Geoneutrino Signal

4.5 to 54.2 geoneutrinos 90%CL
60 TW (99%) upper limit for U and Th

Expected total

Expected total background

(α,n)

Random

Expected Th

Expected U

Candidate Data

Expected reactor

Expected U

Events/0.1 MeV

Anti-neutrino energy, E(ν) (MeV)

Anti-neutrino energy, E(ν) (MeV)
KamLAND is in the wrong place for geophysics, the biggest background for geo-neutrinos is reactor neutrinos
KamLAND provides best limits on energetic $\bar{\nu}_e$


(best limits by a factor of 30)
Other applications of KamLAND


\[ n \rightarrow \nu\nu\nu: \]

\[ ^{11}\text{C}^* \rightarrow ^{10}\text{C}_{GS} + n \]
\[ ^{11}\text{C}^* \rightarrow ^{10}\text{C}^* + n \rightarrow ^{10}\text{C}_{GS} + n + \gamma \ (3.5 \text{ MeV}) \]
\[ \tau > 5.8 \times 10^{29} \text{ yr (90\% C.L.)} \]

\[ n \rightarrow \nu\nu: \]

\[ ^{10}\text{C}^* \rightarrow ^{9}\text{C}_{GS} + n \]
\[ ^{10}\text{C}^* \rightarrow ^{9}\text{C}^* + n \rightarrow ^{8}\text{B}_{GS} + p + n \]
\[ \tau > 1.4 \times 10^{30} \text{ yr (90\% C.L.)} \]
KamLAND $4\pi$ Calibration

Understanding the Detector Response

Event energy $E(r, \theta, \phi)$

Vertex reconstruction $R_{\text{fit}}(r, \theta, \phi)$

Fiducial volume: $R < 5.5$ m

$\Delta R_{\text{FV}} = 5$ cm $\rightarrow \Delta V = 2.7\%$

$\Delta R_{\text{FV}} = 2$ cm $\rightarrow \Delta V = 1.1\%$

Finger box with spools

control cables

calibration pole

$\Delta R_{\text{FV}} = 5 \text{ cm} \rightarrow \Delta V = 2.7\%$

$\Delta R_{\text{FV}} = 2 \text{ cm} \rightarrow \Delta V = 1.1\%$
KamLAND $4\pi$ Calibration System
Calibration with multiple equal-distant $^{60}$Co sources.

→ Allows study of radial dependence of fitter bias
Reduction of Systematic Errors

Current Parameters
Most constraints from $\nu_e$ spectrum due to systematic error on $\nu_e$ rate

Future
Reduce systematic errors for precision measurement of oscillation parameters

→ most precise determination of $\Delta m_{12}^2$
→ improve on $\theta_{12}$ from $\bar{\nu}_e$
The next step for KamLAND: Solar Neutrinos
• Signal and backgrounds:

$^{7}$Be signal now $\sim 10^5 - 10^6$ below backgrounds:

$^{85}$Kr, $^{210}$Bi $\beta$, $^{210}$Po $\alpha$
Control room for purification facility

Purification to begin in fall 2006